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"Scarcity and Growth Revisited;

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Endogenous Technological Change, Natural Resources, and Growth

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In the early 1800s, England's industrial revolution seemed to be in danger of losing momentum as coal supplies dwindled, but rapid growth continued over the subsequent century. In developing countries, many poor cities that have grown at a fast pace have simultaneously experienced rapid growth in air pollution, yet air quality in the large cities of the western world has improved in recent decades. Does growth lead to faster depletion of resources, or does it create the resources to clean up the environment? History, recent or otherwise, shows many possible interactions between growth and scarcity of resources.

The economic forces that shape the interaction between growth and scarcity are substitution and technological change. In their absence, each additional unit of output requires a given amount of resource use, for example energy input, and creates a given amount of pollution; thus output cannot expand without reducing resource stocks and environmental quality. Almost all economists, neoclassical economists in particular, have stressed that the amount of resources needed to produce a given amount of output is not constant on an economy-wide level. Consumers can shift demand to goods that can be produced with less energy or pollution. Producers can switch to techniques that use less resources. As a result, the interaction between growth and scarcity is shaped by consumer preferences and willingness to adjust consumption patterns, as well as by technological possibilities and opportunities for producers.

Limits to growth are then determined by limits to substitution. However, even with ample substitution possibilities, resource substitution is inevitably constrained when resource availability falls: the productivity of human-made inputs falls by the law of diminishing returns. Only technological change can offset the diminishing returns: new opportunities for substitution are opened up by shifts to new, more productive technologies, less resource-dependent technologies, or technologies that rely on completely new resources.

The great waves of economic growth can be attributed to major breakthroughs followed by incremental improvements in technology. The connection to natural resources is obvious when we consider the role of waterpower, steam power (fueled by coal), and the internal combustion engine (powered by fossil fuels). Some technological developments have been due to luck or the genius of an individual. For the most part, however, the commercialization and diffusion of new technologies, as well as their subsequent improvements and alternative applications, have required deliberate investment and a rational business strategy. One of the major innovations in the twentieth century is in fact the introduction of the R&D department. All in all, it is fair to say that a substantial part of technological change is the result of economic investment decisions. Technological change therefore occurs as a reaction to economic incentives and opportunities to develop new technologies over time; that is, technology is endogenous.

Limits to growth must then not only be determined by substitution at a given time, but also by innovation incentives or opportunities for development. Recently, economists have begun to explore the implications of endogenous technological change in formal models of scarcity and growth. Increased scarcity may, through rising prices, stimulate firms to develop new technologies. Thus endogenous technological change may alleviate scarcity limits. But if technological change is costly, it can also be crowded out by resource scarcity. If lower availability of resources reduces the productivity of human-made inputs, it becomes less rewarding to develop complementary new technologies. Scarcity may provide the stimulus to develop new technologies that save on resource input, but at the cost of innovation projects in other directions (for example labor-saving technological change). Changes in the direction of innovation efforts may reduce the effect of aggregate innovation effort on economic growth. Allowing technological change to respond endogenously to scarcity does not necessarily lead to a more optimistic outlook with fewer episodes of scarcity.

This chapter discusses how scarcity can be alleviated by substitution with, or development of, less energy (material) intensive and cleaner technologies. We treat both substitution and technological change as *endogenous* and sort out the determinants behind them. Why does substitution with clean or less resource-extensive technologies not occur when it is technically possible? When does faster growth speed up depletion? When does growth coincide with improved environmental quality? Must policies aimed at improving environmental quality or energy conservation restrict growth? Do more stringent environmental policies induce innovation?

The interaction between growth and scarcity is complex because both growth and scarcity are the result of economic decisions. The direction in which the economy grows determines the effect of growth on resource stocks. Conversely, resource availability shapes opportunities for growth and the rate of return on investment. Economists have analyzed the elementary forces behind depletion and economic growth with simplified models that abstract out many complexities of the real world. To understand the crucial economic forces, we focus on one natural resource at a time, first nonrenewable resources like energy and materials, then environmental resources like fish, forests, clean air, and water. We also aggregate economic activity into a single production activity that requires several inputs, among them natural resources. We focus on theoretical considerations, but we review empirical evidence related to scarcity and growth on the aggregate level.

We first study the effects of changes in production technology on resource use. It turns out that new technologies do not necessarily lead to less depletion. New technologies produce a certain amount of output using less resource (they facilitate substitution), but this implies that they also improve the productivity of resource use. Technological change may thus stimulate the demand for the resource. Second, we turn to the determinants behind technological change itself; that is, we treat technological change as an endogenous variable. We discover when the growth process comes to a halt because of scarcity, and how growth rates are affected by resource policies or environmental policy. Scarcity is likely to crowd out innovation, but knowledge spillovers may offset this tendency.

By moving from nonrenewable to renewable resources, and contrasting exogenous and endogenous technological change, we follow more or less the chronological developments in the literature on growth and resource scarcity. This chapter first reviews models of aggregate growth with a single resource, in the tradition of the economic growth literature (Stiglitz 1974; Dasgupta and Heal 1979). We then extend the scope of analysis to environmental problems and endogenous technological change, and see how the findings of the older literature have to be revised.

Two themes in the recent literature give endogenous technological change a prominent place. One springs from growth theory, in which the assumption of exogenous technological change is considered more and more unsatisfactory. It is unclear whether growth can be sustained if endogenous technological change requires investment and natural resources are essential for production. If resource substitution makes the returns to human-made inputs fall, what happens to the incentive to invest in new technology, also a human-made input? On the other hand, environmental economists have also become interested in endogenous technological change. They realize that the environmental cost of growth might be substantially lower if substitution within given technologies were supplemented by development of new technologies.

We also study market failures in environmental resources, and how they change the role of technological change in mitigating scarcity limits. We discuss the forces behind endogenous technological change, and its implications. Here the central topic is how environmental resource scarcity affects the rate and direction of technological change, and the policy implications. Then we turn to growth models; we are mainly interested in the conditions under which growth can be unlimited despite dependence on natural resources. Finally we discuss how environmental policy affects economic growth.

The Neoclassical Perspective: Nonrenewable Resources

The debate on scarcity and growth has traditionally focused on the scarcity of nonrenewable resources like fossil fuels (oil, coal). "For there to be a meaningful natural resource problem, a resource must be in limited supply, must be nonrenewable and nonrecyclable, essential, and without perfect substitutes" as Stiglitz (1979, *40*) noted when reviewing the neoclassical view of the problem of the scarcity of natural resources. The seminal work of Stiglitz, Solow, Dasgupta, and Heal in 1974 established the benchmark neoclassical framework to study scarcity of nonrenewable resources.[1]

The neoclassical trinity: substitution, diminishing returns, and technological change

In the neoclassical view, the economy can produce only if it extracts resource inputs. Each unit of resources used for production reduces the stock of available resources one-for-one and irreversibly. The stock of resources is privately owned and traded in markets, which also holds for other inputs that substitute for resource inputs (physical capital and labor). Inevitably, production depletes the resource stock. The question is whether such an increase in physical scarcity also implies an increase in economic scarcity: must economic production ultimately fall?

The main message from the neoclassical literature is that substitution of human-made capital inputs for the resource alleviates the economic consequences of physical resource scarcity. The market provides incentives for this substitution: thanks to the existence of markets in which resources are traded, rising prices signal increased scarcity and trigger substitution to less resource-intensive techniques. Capital replaces resources, and limits to growth can be avoided if there are enough substitution alternatives.

The substitution mechanism itself tends to become less and less powerful, however, because the productivity of a piece of equipment tends to fall if a larger amount of capital is combined with fewer resources or other inputs. This law of diminishing returns makes capital accumulation less productive as the amount of available resource inputs falls. So while *substitution* mitigates the drag on growth from resource scarcity, *diminishing returns* constitute another drag on growth. The neoclassical model relies on a third assumption, the presence of ongoing exogenous *technological improvements*, by which growth can be sustained over time. Technological change exogenously improves the productivity of the factors of production—capital as well as resources. It offsets the diminishing returns so that growth can be sustained.

The empirical validity of the neoclassical model is subject to an ongoing debate, discussed elsewhere in this book. Many empirical studies of technological change and substitution on the macro-level directly or indirectly support the neoclassical view. Energy use per unit of production has declined steadily in most industrialized countries over a very long period. Rates of technological change are almost universally impressive.[2] In two studies, Weitzman (1997, 1999) provides an indirect way of testing and calibrating the model. He finds that roughly 40 percent of annualized welfare is the result of technological change, while at most 1.5 percent of income could be gained if the limited nonrenewable resources we rely on were to remain available without limit at today's flow rates and extraction costs.

Depletion of nonrenewable resources and technological change: basic results

What determines the rate of depletion, and therefore scarcity, in a world of substitution? *The resource stock is, in fact, never fully depleted*, neither in the ideal (first-best) situation nor in a market with resource property rights – at least as long as the resource is necessary for production. Society as a whole ideally wants to avoid depletion, because when the resource stock is exhausted, production, hence consumption, is impossible. In extreme scarcity, a small amount of resources is extremely valuable. Full depletion can never be optimal, since society anticipates that it is necessary to preserve some resources to maintain production. Where full depletion looms, society can consume and deplete less today in exchange for a small increase in future consumption.

The avoidance of full depletion is not only optimal, but is also the likely outcome if resource markets function correctly. Individuals own the resource, and they can trade property rights. To secure future consumption, younger generations are willing to buy resource stock from the older generations. When the stock runs very low, the young are willing to pay a very high price, thus giving older generations an incentive not to fully deplete the stock. Forward markets guarantee the dynamic efficiency of the resource market. Market participants may hold incorrect expectations about future scarcity, which may lead to inefficient extraction of the resource. However, market participants are likely to arbitrage away systematically large discrepancies between expectations and realizations. Thus, with the existence of property rights and (forward) markets, there is not much reason for active resource policies.

Some readers will object that individuals may not care enough about the future to conserve resources. When agents discount the future at a higher rate, they tend to speed up depletion by increasing current consumption. Yet, even with discounting, the necessity of the resource for production prevents full depletion.

Exogenous technological change has an ambiguous effect on the rate of depletion. Consider the prospect of a new technology that allows a larger output level for given resource and other inputs. Individuals who anticipate this technological change attach a higher value to the resource stock, since it is more productive in future (younger generations are willing to pay a higher price for property rights). This makes it attractive to conserve more resources for future periods in which the productivity is higher (this is a substitution effect). However, at the same time, a given resource stock can produce more goods, which increases income and makes consumption more abundant in the future. With higher lifetime income due to future technological progress, current demand for resources goes up, since richer households want to consume more not only in the future but also today, that is, they want to smooth consumption (this is an income effect). Thus, substitution and income effects work in opposite directions; society’s preferences will determine which one dominates. Most empirical research on changes in patterns of consumption indicates that income effects dominate substitution effects.[3] Hence productivity gains may raise depletion.

From Old to New Scarcity: Environmental Resources

Since the 1970s, attention has shifted from the scarcity of materials and energy resources to the scarcity of environmental resources like clean air, clean water, clean soil, forests, fish stocks, and rare species.[4] Economists have attempted to analyze the scarcity of environmental resources within the framework they developed for nonrenewable energy and mineral resources. Certainly, the two types of natural resources have some features in common—they are inputs in production processes and they can in principle be depleted. But environmental resources are not priced or traded in markets, and their use has much in common with public goods. Consequently, environmental resource scarcity may pose bigger economic problems than scarcity in nonrenewable resource markets.

The characteristics of environmental resources

When we claim that environmental resources are an input to production, the connection is less direct than that between energy or materials and production. Production creates pollution, a byproduct that diminishes environmental quality. Pollution can therefore be regarded as the inevitable depletion of a resource stock due to production. In this sense, pollution is similar to resource use in the standard neoclassical approach. Pollution is often linked to a particular input, for example chemicals, which cause toxic waste, or energy use, which pollutes the air. Substitution between polluting inputs and other inputs takes place because firms can choose to undertake abatement activities, which reduce pollution or mitigate its effects. Technological progress may result in cleaner production processes, products that generate less waste when consumed, or more efficient (cheaper) abatement technologies such as filter, scrubbers, and other add-on technologies.

We commonly distinguish environmental resources from mineral resources because the former are renewable and the latter are nonrenewable. Pollution creates environmental resource scarcity, but the damage need not be long lasting, since nature has a capacity to neutralize pollution. For example, soil and river water pollutants can be diluted and flushed out by rainfall. The pollution absorption capacity of ecosystems, though not unlimited, makes environmental quality a renewable resource.

The stock of environmental resources may bear directly on society's welfare. We care about the environment as an amenity: unique landscapes and species, clean air, and attractive sites. We care about mineral resources only indirectly as inputs to production of goods that we value, but we care about environmental resources directly. Some industries might benefit from cleaner water supply: with lower water treatment costs, they might produce useful goods more cheaply. But clean water resources directly benefit consumers in the form of health benefits and amenity values.

Environmental resources are public goods. While nonrenewable resources like oil and minerals are traded as private goods in markets and protected by property rights, it is impossible to define the owner or enforce property rights of environmental resources like clean air, ocean fish stocks, or the ozone layer, and it is not straightforward to charge users of these resources. The essential properties of public goods apply to environmental resources: access is hard to exclude, and consumption is nonrival. Here markets fail, and the price mechanism on its own cannot ensure that environmental resources are allocated and used in the best way for society: as long as users do not need to pay a price, they do not internalize the social cost of resource depletion and environmental degradation. This calls for public intervention, like pollution taxes or fish quotas, to correct the resource market externalities.

Environmental degradation and technological change: basic results

We can modify the standard neoclassical model to reflect the connection between production and environmental resource depletion. We have to account for not only the renewable character of environmental resources, but also for the public goods character: markets for resources are missing, but regulation may repair resource externalities.

To analyze environmental degradation, it is useful to deal separately with two cases. In the "first best case," institutions and regulation ensure best use of environmental resources. Society trades off degrading the environment for the sake of production against maintaining environmental quality for the sake of its amenity value and its future resources. In the "unregulated market case," market prices fail to reflect scarcity. Firms are typically not charged the full cost of depletion of resources. If firms are allowed to pollute more, their unit production cost is lower and productivity is higher. They maximize profits by expanding production until the marginal product of additional natural resource use (read pollution) is zero. Clearly, if the environmental asset is provided for free, undesirably high levels of production, and pollution, result. Between these extreme cases, regulation addresses some of the externalities, but is inadequate to attain the socially efficient situation.

Without adequate resource policy, environmental resources are easily over-exploited. If the resource becomes scarcer, the price does not reflect this, and firms or individuals have no private incentive to reduce their consumption. Profitable low-cost options may be available to reverse environmental degradation, but individual agents would ride free on the investment of others in the public good. Without price signals, substitution possibilities are not exploited. Technological change may also fail: if agents do not pay to pollute, there is no incentive to develop cleaner technologies.

Without adequate resource policy, technological change is likely to speed up environmental degradation. With adequate resource policy, the effect of technological change on the environment is ambiguous, as we have seen when we discussed the conflict between the substitution effect and the income effect in the context of nonrenewable resources. However, in the absence of resource policy, firms extract resources without concern for future resource scarcity. They have no reason to conserve resources exploit future productivity improvements. The substitution effect no longer applies, but the income effect does, which speeds up resource degradation.

Technological change can be *neutral* or *biased*. Neutral technological change raises the productivity of all conventional (nonenvironmental) inputs in the same magnitude. For example, firms may improve the organization of their production process so that more outputs are produced from the same inputs, or they may redesign products without changing input requirements, making them more attractive to customers. The marginal products of all inputs, including polluting inputs, will rise, and firms will want to consume more of all inputs, unless prices change. Without a price on pollution, however, pollution must increase. Neutral technological change makes it possible, in principle, to produce the same amount with *less* pollution, but this gives firms the incentive to pollute *more* because the productivity of pollution rises.

Biased technological change affects the productivity of one input more than another. An improvement in the design of gas-guzzling cars that draws customers away from other less polluting cars implies a higher productivity of energy, and polluting inputs in particular; such a resource-biased technological improvement makes consumers tend to spend more on gasoline. In contrast, a cost reduction for production of low-emission vehicles might reduce the expenditure share of gasoline—a technological change classified as resource-saving.

Without regulation, new technology improves environmental quality only if:

- the new technology decreases the unit production cost (which excludes the environmental cost if the environment is not priced). If not, the firm is better off with the old technology and will not adopt the new one. Producers pass on the decrease in unit costs as lower prices, which result in larger production.
- the new technology substantially reduces the marginal productivity of polluting inputs. If not, firms may either increase or decrease pollution per unit of output, but due to the expansion of the scale of output, total pollution will still increase (the rebound effect).

Market-based instruments can trigger resource-saving innovations. In particular, incentives for adoption of cleaner technology change if regulation imposes a cost per unit of pollution, such as a pollution tax or a system of tradable pollution permits. Whether the regulation is stringent enough to produce the social optimum or not, firms have an incentive to avoid pollution up to the point where the marginal returns to pollution equal the pollution tax or the price of a tradable permit. Suppose regulation imposes a pollution tax, fixed at an arbitrary level. Now technological change occurs; if it takes the form of improvements in total factor productivity, pollution will increase because the marginal productivity of pollution is increased, but the cost remains the same.[5] On the other hand, if technological change results in lower costs of reducing pollution (improvements in abatement technology), firms reduce pollution.

It may well be optimal for a growing economy to aim at improving environmental quality. That is, society should expand environmental resource availability, rather than deplete. In a growing economy, consumption goods become more abundant, so they are valued at a lower marginal utility relative to environmental amenities. This increases the demand (willingness to pay) for environmental quality. In other words, the demand for both consumption and environmental quality goes up with income (economists have called this the “normal goods” property). Economic growth calls for higher environmental quality as long as there is some “satiation” in preferences with respect to produced consumption goods (Lieb 2002). When the availability of produced goods is lower than environmental quality, as may be the case in poorer countries, society gives priority to increased production at the expense of environmental quality. When income grows large enough, demand should shift to environmental quality.

In the long run, environmental resources are conserved in the optimum. Whereas in the standard neoclassical model the nonrenewable resource stock is never fully depleted because extractions from the stock are essential to production, in the case of renewable resources it is the stock itself that is essential. Environmental quality serves as an amenity in utility and as a productive asset in production: clean air is essential for health and for workers’ productivity; soil quality is essential for agriculture. Environmental resource stock is not asymptotically depleted, but under normal conditions a nonzero optimal stock of environmental resources is approached in the long-run social optimum.[6]

Some empirics: the Environmental Kuznets Curve

The main evidence on environmental resource scarcity and economic growth comes from the literature on the Environmental Kuznets Curve (EKC) hypothesis.[7] The relation between pollution and income is characterized as an EKC if pollution first rises with income, then declines when income exceeds a certain threshold.

There is no theoretical reason to expect pollution and growth to be unambiguously related, because both income and pollution are endogenous variables (Copeland and Taylor 2003). The pattern of growth, choice of technology, and nature of technological change determine how income and pollution evolve over time, and a host of underlying factors can affect both variables. However, our review of basic theory will help us to sort out the basic forces that affect pollution and environmental degradation in the process of growth.

Note that the theory predicts an EKC pattern under two specific alternative sets of circumstances:

- if environmental policies reflect social preferences for growth and environment, and thus boost the demand for environmental quality as "normal goods."
- if for low income the productivity of polluting inputs increases, but for higher income it falls.

Indeed for water pollution and several types of air pollution, e.g. sulphur dioxide (SO_2), suspended particulate matter (SPM), and oxides of nitrogen (NO_x), most studies agree that the relationship between per capita income and pollution per capita is inverted-U-shaped. There is mixed evidence of an EKC pattern for deforestation, but here variation in income level seems to be relatively unimportant in explaining deforestation differences among countries. Municipal waste, carbon dioxide (CO_2) emissions, and aggregate energy use are all monotonically related with income. It should be noted that the results are far from conclusive. Most estimates stem from multi-country analyses, so we cannot immediately discern the relationship between growth and pollution. Moreover, the results are biased because of selective data availability: typically, data are collected only for pollutants that are considered a problem for sufficiently long a period in many countries.

The evidence that emissions fall with income growth is limited to a small number of pollutants (local pollutants with immediate health effects) and to higher income countries. The preceding theoretical considerations partly explain this. In an economy in which pollution is unregulated, it depends on the nature of growth and technological change whether pollution falls over time. Indeed, if economies grow in early stages by accumulating polluting capital and in later stages rely on clean human capital, the EKC might emerge as a byproduct of the pattern of growth. Similarly, the EKC can be explained as a byproduct of the structural change that accompanies growth. Following a transition from agriculture to manufacturing, industrial pollution grows with income; a subsequent shift from manufacturing to services may explain the cleaning-up phase of the EKC. Empirically, this latter effect turns out to be weak, however. Structural change has lost most of its momentum in OECD countries in the last decades. Most reduction in pollution intensity takes place *within* the manufacturing sector. Moreover, the computerization of the service industry points out that services may become more energy- and material-intensive than suggested by the simple theory.

When we connect our insights about technological change and environmental resource scarcity to the empirical findings, two clear conclusions emerge. First, despite the discovery of an EKC for several pollutants, pollution will not decline automatically as an economy grows richer; we may find an EKC pattern only because richer economies implement more stringent environmental policies. Second, reduced pollution is more likely the result of a deliberate change in technology, rather than a byproduct of technological change or growth.

From Manna-from-Heaven to Innovation as an Economic Decision

Technological change is an essential driving force behind economic growth and a powerful mechanism to mitigate the cost of resource scarcity. So far, we have discussed only the effects of technological change. Now we turn to the determinants of, and the driving forces behind, technological change.

The economics view of technological change has altered markedly over the past few decades. Economists long treated technological change as too complex to explain on an economy-wide level starting from the economist's standard assumption of competitive markets. However, commercial research and development are increasingly important strategies in multinational corporations and small firms in new product markets. Industry leaders and national policy makers stress the role of innovation for national wealth and competitiveness. The way Japan in the 1960s and other Asian industrializing countries later on achieved rapid growth suggests that policy and economic incentives can influence the pace of technological change within a nation.

All this has led economists, and growth theorists since the late 1980s in particular, to view the pace and direction of technological developments as the outcome of economic decisions rather than an unexplained fact of life. The process of growth as well as the reactions to changes in economic environments (such as increasing scarcity) can be much better understood if technology is seen as an endogenous rather than exogenous variable. When the path of technological change was fixed, firms and individuals could react to changes in resource availability only by changing the allocation of economic activity; resource scarcity would trigger only substitution. However, with endogenous technology, innovation may be intensified or redirected in response to economic changes.

Economists have tried to incorporate endogenous technology into the neoclassical growth framework. This involves a major change—abandoning the idea of perfect competition. Economists have identified new market failures and public goods and property rights problems when shifting from exogenous technology to endogenous technology. These externalities interact with resources externalities introduced with the shift from modeling nonrenewable resources to environmental resources.

Innovation incentives and opportunities

Little technological change would take place if no effort were spent on innovation (in the form of, for example, inventive activity, research and development expenditures, building prototype factories). Deciding how much effort to spend on innovation requires the calculus of costs and benefits. The cost of innovation consists of the costs of inputs in the innovation process: laboratory equipment and tests, but mainly time and engineering labor. The returns are the discounted expected profits reaped once the innovation is put in the market. The development of new knowledge (a new idea, a blueprint for a new product or technology) typically has a fixed cost character. Incurring a one-time investment cost is sufficient to develop a new idea, which can subsequently be applied and put into practice many times at no additional cost. Hence, the size of the market determines the rate of return, which implies increasing returns.

Innovators balance costs and expected benefits in determining how much to spend on what kind of innovation projects. Hence, with endogenous innovation, the direction (bias) of technological change is endogenous. Innovators choose among different investment projects; some improve the productivity of resources, while others improve the productivity of capital or reduce the costs of extraction, and so on.[8] The higher the expected returns and the lower the innovation costs in a particular project (direction), the more innovation will take place on this project (in this direction). By this mechanism, high prices for certain inputs shift innovation efforts to projects that develop technologies that save on these inputs. Relative price may affect the direction of technological change, which is known as the *induced innovation hypothesis*.[9]

Market failures show up at various stages of the innovation decision, because of *monopolistic product markets*, *knowledge spillovers*, and *creative destruction*.

- Imperfections in the product market arise because innovation requires monopoly power: no firm or individual will invest in developing a new technology unless it can appropriate the returns by making users pay for it, and exclude those who will not pay. The monopoly profits are the carrot for the innovator, and thus enhance dynamic efficiency. However, they burden society with prices above marginal production costs at the cost of static efficiency.

- Knowledge spillovers occur when agents can benefit from new knowledge developed by other firms or research institutions without (fully) paying for it. Knowledge is hard to exclude by means of tight property rights. Patent laws may keep producers from using blueprints to produce a specific product or use a specific technique, but it is hard to prevent use of the more general knowledge that can be inferred from the blueprints. Current innovators build on knowledge developed by earlier innovators, without compensating them. Imitation and patent infringement is another reason for knowledge spillovers. Intertemporal knowledge spillovers mean that the innovator can appropriate only part of the social returns, and the incentive to research is suboptimally low.
- There are also inducements to overinvestment in R&D: several firms may race for the same patent, and duplication of research effort takes place. Innovating firms may replace other firms before these have recouped their investment costs. Such a process of creative destruction may impose a social cost, since the innovator does not internalize the cost it imposes on the other firms.

In theory, we cannot say which type of externality dominates. However, the consensus from the empirical literature is that the positive externalities dominate and that the social rate of return to innovation exceeds the private return.[10]

Resource scarcity and endogenous technology: basic insights

A large endowment of resources has an ambiguous effect on the rate *of innovation*. On the one hand, abundant supply of production factors makes it more attractive to develop new knowledge that increases the productivity of these resources; the returns of R&D rise with the scale at which it is applied, but the cost of developing new knowledge is independent of scale: knowledge is nonrival and development is a fixed-cost activity. On the other hand, however, the opportunity cost of R&D also rises: with more (nonlabor) resources available, the marginal product of labor in production grows, which makes it attractive to allocate labor to production rather than to research.

Induced technological change compensates for low substitution possibilities: the poorer substitution (between natural resource inputs and other inputs) is, the more likely the *direction* of technological change shifts to the scarce factor. Lower resource availability drives up the prices of marketed resources. This results in higher prices of resource-intensive goods as well, which makes it attractive to invest more in innovation in resource-intensive sectors. However, the price effect may be counteracted by a market size effect: lower resource availability reduces output in resource-intensive sectors and makes innovation in these sectors less attractive. With less production in the sector, the scale at which a new technology can be applied is smaller. Which effect dominates depends on the combined price and quantity effect of lower resource availability on revenue and profits in the sector, since innovation shifts to the sector in which profits of innovation increase. If goods from other sectors easily substitute for resource-intensive goods, the price increase due to lower resource availability will be small, revenues in resource-abundant sectors will fall, and innovation will shift away from these sectors. In contrast, if goods from other sectors poorly substitute for resource-intensive goods, revenues in the resource-intensive sector will rise and innovation will shift to these sectors. In both cases, however, innovation results in lower demand for energy: in the case of poor substitution, because innovations are directly energy-saving; in the case of good substitution, because innovation makes substitute goods in energy-extensive sectors cheaper and demand shifts further to these sectors.

Resource market failures may cause induced technological change to inefficiently speed up environmental degradation and depletion. Because market responses determine technology choices, before resource scarcity can stimulate innovation, resources markets must exist and function efficiently. Markets for fish exist, but excessive catch is likely to result because world fish stocks are not governed by property rights. If inadequate fishery management causes fish populations to decline, fish prices will go up. This could actually stimulate investment in new fishing technology and more powerful vessels. Hence, in a situation of excessive harvesting, induced technological change might even increase harvesting and depletion. The technological change moves in the “wrong” direction.

Technology responds to scarcity in an efficient way only if resource and environmental policies provide adequate price signals. But policy itself has to be in place. It may be that environmental problems induce policy changes, which in turn induce technological changes. The *induced policy response* seems to be empirically important, as is discussed above in the context of the Environmental Kuznets Curve.

Some empirics on energy, environment, and innovation.

Studies of the correlation between resource endowments and economic growth produce mixed results, in line with theory. Resource booms have often deteriorated rather than improved economic performance in, for example, Latin America (Sachs and Warner 2001). However, resource-rich countries like the United States and Norway provide counterexamples. Wright and Czelusta (2002) attribute the U.S. growth success to a combination of large resource availability and targeted investment in skills and new technologies. Institutional quality and the correct innovation incentives prove to be essential in transforming resource availability into wealth and coping with problems of resource scarcity. Easterly and Levine (2003) find that the apparently adverse effects identified by Sachs and Warner only arise when the concentration of resource wealth is associated with corruption and weak institutions.

Empirical studies into the link between environmental regulation and innovation typically find ambiguous results, again as predicted by theory. Research and development expenditures tend to rise with environmental compliance expenditures, but there is no correlation with innovative output as measured by patent applications (Jaffe and Palmer 1997).

There is some support for the induced innovation hypothesis for environmental innovation. Lanjouw and Mody (1996) find that increases in environmental compliance cost lead to increases in the patenting of new environmental technologies with a one- to two-year lag. This finding supports the poor substitution case: the price effect dominates the market size effect, which spurs innovation. There is also evidence that energy-saving technological change was especially important in periods of high energy prices and oil shortages (Kuper and Van Soest 2003).

Empirical studies point out that price changes and regulation explain only a relatively small part of the bias of innovation. Newell et al. (1999), for example, find evidence for the role of energy prices, regulation, and market size in directing innovation. However, up to 62 percent of the total change in energy efficiency must be attributed to other factors. They also find no effects of these three factors on the overall rate of technological change. Similarly, Popp (2001) finds that two-thirds of the change in energy consumption with respect to a price change is due to simple price-induced factor substitution, while the remaining third results from induced innovation. Popp (2002) finds evidence for knowledge spillovers: using patent citation data, he finds that innovations directed at energy improvements build on the total stock of knowledge embodied in the (quality-adjusted) stock of patents for energy efficiency improvements. He also finds, however, that there are diminishing returns with this stock of knowledge. One of the very few economy-wide studies on the bias of technological change, by Jorgenson and Fraumendi (1981), finds that the majority of sectors in the U.S. economy have experienced technological change that not only saved material but used energy.

In a famous article, Michael Porter (1991) argued—on the base of case studies—that environmental regulation often increases profits of firms, because of first-mover advantages or because of the elimination of waste of input use. The economics profession has reacted sceptically. Environmental regulation restricts firms in their behaviour and reduces their menu of choices. The Porter hypothesis seems to claim that firms choose an action from this smaller menu that gives higher profits than the action they would have chosen from the larger choice set available in the absence of regulation. But then it becomes unclear why firms did not choose this action without the regulation. In a world with endogenous technological change and knowledge spillovers, the Porter hypothesis may be valid, however, since technology, productivity, and profits of an individual firm now depend on aggregate innovation activities and knowledge stocks, which may change in reaction to environmental regulation. Unregulated firms' R&D strategies are suboptimal because of knowledge spillovers and other market failure in markets for technology. Environmental regulation may improve the incentives for innovation, thus improving not only social welfare, but perhaps also firms' profits.

Limits to Growth?

Despite substitution and technological change, dependence on limited resources may ultimately result in declining economic output. Limits to growth can be avoided if incentives to accumulate capital substitutes for resources and to innovate new technologies continue, even when resources become scarcer. To understand limits to growth, we have to examine long-run incentives to investment and innovation, and how they change if the economy grows and resource stocks change. Regulation affects incentives, so we must distinguish between situations without inadequate intervention and those with optimal policies that address market failures.

Long-run growth, capital accumulation, and exogenous technological change

Capital accumulation allows society to invest in substitutes for natural resources. Individuals choose to invest up to the point where the marginal product of capital equals their required rate of return, which reflects their impatience (utility discount rate). They accumulate more capital the more patient they are and the less quickly the returns to capital fall with accumulation. The following basic results emerge in the neoclassical model.

First, substitution of capital for the depleted resource can prevent falling output. But without technological change, output is still likely to fall unless very stringent conditions apply. If substitution of human-made capital for resources is poor, the accumulation of capital cannot prevent production falling in the long run. If substitution and the production elasticity of capital are sufficient, a constant level of production can in principle be sustained in the absence of exogenous technological progress (Solow 1974; Hartwick 1977). Even then, without government intervention individuals who maximize the discounted lifetime utility will not find it optimal to accumulate enough capital to sustain this constant level of income.[11] In other words, while nondecreasing production is feasible, it is not optimal. As we have seen before, the complementarity between resources and capital, together with the diminishing returns with respect to capital, imply that the returns to capital fall when more capital is used per unit of resource use. With the decline in the rate of return, investment falls and output ultimately declines.

Second, with a constant rate of exogenous technological change, growth and capital accumulation can be sustained. Technological change increases the productivity of capital and offsets the fall in returns due to capital-resource substitution. The presence of technological change is not sufficient. If resource–capital substitution is poor, the nature of technological change has to be resource-saving, increasing the productivity of capital more than the productivity of the resource.[12] The technological change has to be rapid enough to counteract the fall in returns to capital. Accordingly, the faster capital accumulates and the poorer substitution is, the more rapid the change must be.

Third, ongoing technological change can sustain growth only if environmental policy is rigorous. In particular, in a growing economy, the tax on pollution must increase over time to prevent environmental degradation. Environmental resources are bounded, so pollution must be bounded to ensure that environmental resources are not completely depleted. In contrast, the stock of human-made assets expands continuously in a growing economy, driven by improvements in total factor productivity. With more human-made capital per unit of polluting input, the productivity of polluting inputs rises. To keep firms from increasing pollution, they have to face higher costs of pollution.

Fourth, with capital accumulation and depletion driven by exogenous technological change, preferences affect long-run growth and depletion rates. Lower discount rates reduce the pace at which the resource stock is depleted and speed up long-run growth. Faster technological change also boosts growth.

How to interpret capital and technological change in the neoclassical model

Capital, the key variable in the neoclassical model, is sometimes narrowly understood as machines and hardware. However, we would do more justice to the spirit of the neoclassical approach by interpreting capital in a broader sense, namely as forgone consumption. Today's consumption is given up for the sake of new assets. Investment not only gives rise to a physically larger mass of machines, but also to better, more efficient machines and organizations, perhaps even to new social attitudes toward waste of energy. The assets allow production of at least the same services with less use of scarce nonrenewable resources. Assets thus comprise not only capital in a narrow sense, but also intangible assets and knowledge; similarly, not consuming implies investment and innovation.

The broad interpretation of capital clarifies the neoclassical assumption of substitution between capital and resources like oil and materials. An expanding capital stock is not necessarily a collection of more and more of the same type of machines. Instead, capital is knowledge frozen in material, not just material; capital embodies the knowledge stock, and this knowledge stock expands in the process of accumulation. With a larger capital stock, production might require less material or lower total energy inputs, because the replacement of old machines by new ones puts into practice new ways to harvest energy, to use materials, and so on. A larger capital stock produces new products and satisfies new wants, which may require less energy and materials. Thus conceptualized, capital does not so much provide the capacity to produce a given physical object as provide the capacity to create valuable things, where the exact nature and physical properties of these things may change.[13] Society can give up consumption in order to create assets that generate more future value and replace resources. The degree of substitutability determines the degree to which this dematerialization is possible.

This broad interpretation of capital brings up some problems, however. The standard neoclassical framework treats investment as a single homogenous activity. It does not explicitly model investment as a joint process of the creation of new knowledge and the embodiment of new knowledge in capital goods.

All investment is still treated as an activity that requires the production and trade of private goods for which there are well-defined markets—perfectly competitive markets even, according to the model. Although this may hold true for equipment and mass-produced machinery, this is less likely to apply to knowledge. As argued above, knowledge has a public good character, is subject to increasing returns, and gives rise to monopolistic markets. Thus the neoclassical model sweeps some important sources of market failures under the carpet.

In the broad interpretation of capital in the neoclassical model, forgone consumption results in not only physical capital accumulation, but also endogenous technological change. Paradoxically, according to the model, endogenous technological change cannot prevent growth from falling due to diminishing returns, while exogenous technological change does exactly the opposite and is introduced in the model to keep growth going. If no exogenous changes in technology took place and all technological progress resulted from forgone consumption converted into intangible assets, diminishing returns to capital (now including knowledge capital) would cause incentives to accumulate (now including the incentives to innovate) to fall over time. Thus, endogenizing innovation seems to change the role technological change plays in alleviating scarcity limits.

We can imagine three solutions to this paradox. First, the pessimistic view is to simply conclude that scarcity puts limits to growth because innovation is not automatically arriving as manna-from-heaven; it requires effort, the returns of which inevitably fall with the depletion of resources and the need to reduce pollution. Thus the endogeneity of technological progress undermines one of the central results from the standard neoclassical approach—the power of the price mechanism—using its own cornerstone—diminishing returns. As a second solution, recent developments in growth theory have suggested that returns to investment are no longer diminishing if we take into account the accumulation of intangible goods with the character of public goods, like knowledge. This indeed generates ongoing growth if we can abstract from natural resources. However, even with constant returns to the broad concept of capital in production, if production requires nonrenewable resource inputs, growth cannot be sustained unless there is another exogenously growing factor, e.g. population growth or technological change (Groth and Schou 2002). Only if production requires only renewable resources, and if society keeps constant stock of them, can growth be sustained with constant returns. In a third and more appealing solution, we treat innovation as a separate activity. That is, the production function of new ideas (the R&D technology) is completely different from the production function of equipment and physical capital goods (Bovenberg and Smulders 1995, 1996; Aghion and Howitt 1998). Then, if resource inputs are not important as an input in R&D, growth can be sustained. It is this approach that we consider next.

Endogenous technological change and endogenous growth

By explicitly introducing endogenous technological change into the neoclassical model, we can study the incentives for technological change. Technological progress requires considerable investment effort in the form of learning or research and development. Whether innovation is sufficiently fast to make growth sustainable thus depends on innovation opportunities and incentives.

The standard approach to endogenous technological change is the *endogenous growth framework.*[14] This assumes that a third asset is relevant for production: not only the stocks of resources and capital, but also the stock of knowledge. Expansions of the physical capital stock and the knowledge stock require different types of investment. New productive knowledge is created when firms undertake research and development activities. Knowledge is a nonrival factor of production: it raises the productivity of the capital and resource inputs. The production of new knowledge—the innovation process—requires that some consumption is forgone: workers have to devote their labor effort to research instead of final goods production, or some of the output of the economy serves as an intermediate input (research lab equipment) in R&D. In addition, knowledge is an input in R&D. Current research builds on the achievements of past research.

The key assumption in the endogenous growth framework is that forgoing consumption in order to accumulate productive human-made assets no longer runs into diminishing returns, because current research builds on past research. A higher stock of knowledge makes research so much easier that no matter how large the stock of knowledge grows, the returns to investment in new knowledge remain constant.[15] A society willing to spend enough on R&D can realize a steady rate of technological change sufficient to offset the diminishing returns from capital-resource substitution and sustain long-run growth. If the private returns to innovation are large enough, the economy can grow without bounds as in the standard neoclassical model, but without relying on exogenous technological change.

In most models of endogenous growth and natural resources, the market generates too little innovation, too little growth, and typically suboptimal depletion. Whether depletion is too slow or too fast depends on the income and substitution effects. Inadequate innovation affects the incentives to deplete, as we discussed above in the context of an exogenous change in innovation. In the empirically relevant case, in which income effects dominate intertemporal substitution effects, this results in depletion at a slower pace than in the social optimum. The best policy is to subsidize research and development, which will increase growth. The optimal technology policy can be expected to speed up both depletion and growth as well as innovation: individuals anticipate higher consumption levels and respond with faster depletion to smooth consumption.

In the endogenous growth framework, society can grow without bound and at the same time maintain a stable level of environmental quality. However, there is a trade-off between the rate of growth and environmental quality. Society may prefer low growth, or even constant output, in order to maintain high environmental quality. On the other hand, societies that care little about the future (discount at high rates) may optimally choose to produce at high current levels, deplete resources, and let environmental quality decline to low levels. So, while technological opportunities are less constraining because of the absence of diminishing returns, society's preferences and willingness to take action, its capability to implement resource and technology policies, become much more crucial for scarcity.

Conclusions

This chapter has reviewed several aspects of endogenous technological change and how it affects the tension between growth and scarcity. Substitution and technological changes are the main ways to alleviate scarcity in the neoclassical approach. Since resource substitution is likely to run into diminishing returns, the offsetting force of technological change is necessary to sustain growth.

Technological change does not guarantee a win-win outcome, though. When technological change comes free, it is not necessarily conducive to resource conservation or environmental improvements. Technological change that improves the productivity of resource inputs alleviates scarcity and boosts growth, but it also increases the demand for resources and may raise total depletion or pollution by a rebound effect. The form of technological change is crucial: technological change in abatement technologies, for example, does reduce pollution.

Technological change is to a large extent the result of economic decisions, so the rate and direction of technological change is affected by resource scarcity. Recent developments in endogenous growth theory change our understanding of scarcity and growth, since it treats technological change as a costly process, in which innovators trade off costs and expected benefits, and which is subject to market failure and spillovers. Technological improvements necessary for sustainable growth cannot be assumed to continue to arrive without cost. Given market failures, market responses cannot be expected to ensure technological change at a sufficient rate and in the right direction; regulation must be invoked. First, policies should create efficient resource markets and impose marked-based instruments, such that prices correctly reflect scarcity of natural resources. Then profit-maximizing entrepreneurs and innovators will have an incentive to develop cleaner, resource-saving technology. Second, technology policy is needed since the returns of innovation are hard for private investors to secure; compensating innovators for spillovers by means of research subsidies or innovation rewards will more accurately reflect the social value of innovation.

If technological change responds to market signals, policies can induce technological change in response to increased resource scarcity. But increased scarcity of resources may slow down the overall rate of endogenous technological change, which could aggravate scarcity. The productivity of human-made capital and other inputs falls if complementary resource inputs decline. As a result, the returns to investment fall, not only with respect to capital investment, but also investment in new technology.

Endogenous technology makes policy important, much more than is suggested by the standard neoclassical approach to scarcity. Finding the exactly right policy is that much harder, and policy mistakes have potentially large adverse effects. Policy not only affects depletion and substitution directly, but may also crowd out innovation or shift technological change in the wrong direction, which in turn affects depletion and substitution. Differences in policy among countries also have more persistent effects: once an economy has adopted and adjusted to certain technologies, it is costly to change to fundamentally different technologies. Countries may become locked in resource-intensive production structures, a problem if resources are depleted rapidly or demand for environmental amenities rises. Countries that have chosen a growth strategy based on human capital rather than natural capital may be better off in the long run. Such scenarios differ markedly from the standard neoclassical view on growth, in which technology is a public good, freely available for all and producing convergence among countries.

Technological change is essential to sustain growth, especially in the presence of resource scarcity. Technological change has been pervasive and effective in the past. There is no reason to expect this will change as long as human creativity, flexibility, and adaptability, combined with knowledge spillovers, provide us with new ways of production and organization. However, economies cannot flourish until policymakers acknowledge scarcity and market failures, apply innovation incentives to solve natural resource problems, and translate vision into policies for a sustainable economy.

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Notes

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[14] Seminal contributions in this tradition are Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992, 1998).

[15] Schou (1999, 2000); Aghion and Howitt (1998, chapter 5); Scholz and Ziemes (1999); Barbier (1999).

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